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Nutrient budgeting as an approach to improving nutrient management on Australian dairy farms

C. J. P. Gourley[A,E], J. M. Powell[B], W. J. Dougherty[C] and D. M. Weaver[D]

[A]Department of Primary Industries, Ellinbank Centre, 1301 Hazeldean Road, Ellinbank, Vic. 3821, Australia.
[B]USDA Agricultural Research Service, US Dairy Forage Research Center, 1925 Linden Drive West, University of Wisconsin, Madison, WI 53706, USA.
[C]NSW Department of Primary Industries, Locked Bag 4, Richmond, NSW 2753, Australia.
[D]Department of Agriculture and Food, Western Australia, 444 Albany Highway, Albany, WA 6330, Australia.
[E]Corresponding author. Email: cameron.gourley@dpi.vic.gov.au

Abstract. Dairy farming in Australia continues to intensify. Increased stocking rates have resulted in increased milk production per ha, but have also required greater inputs of purchased feed and fertiliser. The imbalance between nutrient inputs, primarily as feed and fertiliser, and nutrient outputs, in milk and livestock, has resulted in significant nutrient accumulation on dairy farms and, consequently, a greater risk of nutrient loss to the environment.

Nutrient budgeting is a technique used to quantify or predict nutrient deficits or surpluses, either at a whole-farm or field scale, in an attempt to improve nutrient use efficiency and reduce nutrient losses from agriculture. A broad range of nutrient budgeting approaches are used internationally, and depending on their purpose, they vary from the very simple to the very complex. Nutrient budgeting has been widely used to assist on-farm nutrient management decisions, in research to identify major nutrient pools, transformations and losses, to enable farmers to access cost-sharing support from governments, and in some countries as a major regulatory tool.

The changing nature of Australian dairy operations, the increasing societal pressure on the farming community to reduce nutrient losses to water and air, and the need to provide evidence that farm practices are meeting environmental standards, justifies the need for improved nutrient management practices on Australian dairy farms. This paper describes different types of nutrient budgeting approaches used internationally and assesses the benefits of developing a practical, scientifically rigorous and nationally standardised nutrient budgeting approach for the Australian dairy industry.

Additional keywords: nitrogen, phosphorus.

Introduction

Modern agriculture is a significant contributor of nutrients to land, water and air. Although nitrogen (N) and phosphorus (P) inputs are required for most dairy operations, when used in excess they can significantly degrade air and water quality. P losses from dairy farms occur mainly through surface water transport and to a lesser extent leaching to ground water, leading to eutrophication of water storages, lakes and rivers. N losses include the volatilisation of ammonia, resulting in particulate formation (haze) in the atmosphere and subsequent redeposition, acidification and eutrophication of surface waters, the emission of the potent greenhouse gases NO and NO_2, and nitrate leaching into surface and ground water.

The risk of nutrient pollution from a dairy farm increases when nutrient inputs exceed the amount of nutrients leaving the farm in products. Total P and N inputs onto dairy farms, mainly in the forms of feed, fertiliser and N fixation by legumes, are usually much greater than the outputs of P and N in milk, animals and crops (Satter 2001; VandeHaar and St-Pierre 2006). These surpluses tend to increase as farms intensify and stocking rates increase (Halberg *et al*. 2005*a*).

In addition to off-farm environmental impacts, nutrient accumulation on dairy farms can result in unnecessary expenditure on feed supplements and fertiliser, and may impact on animal health and production. Excess P on dairy farms can result in increasing soil P levels beyond agronomic requirements (Weaver and Reed 1998; Gourley 2004; Mekken *et al*. 2006), which may also increase the concentration of dissolved P in surface runoff (Sharpley 1995) and leachate (Fortune *et al.* 2005). Unlike P, N is not significantly buffered by soils, and where N is applied in high concentrations such as in dung, urine or fertiliser, losses through volatilisation and leaching can be high (Rotz *et al*. 2005). Excess potassium (K) can accumulate in soil and feed, and can cause severe metabolic disorders in ruminants (Rooney *et al*. 1977).

Over the past 20 years, a range of environmental policies have been developed and implemented in Europe and the USA,

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and more recently in New Zealand, with the aim of reducing nutrient losses from dairy farms to the environment. Central to many of these policy approaches has been the development and on-farm implementation of nutrient budgeting tools. A more holistic approach to dairy farm nutrient management is necessary in Australia, encompassing the needs of farmers to meet production goals, assisting to identify opportunities for improvements in nutrient use efficiencies, and reducing the risk of off-farm nutrient impact.

The objective of this paper is to: (i) discuss the need for improved nutrient management for the Australian dairy industry and the potential contribution of nutrient budgeting to this objective; (ii) outline different nutrient budgeting approaches and their applications; and (iii) suggest possible improvements to existing nutrient accounting approaches, which may improve their adoption and use on Australian dairy farms.

The need for improved nutrient management on Australian dairy farms

Australia is the third largest milk exporter after Europe and New Zealand and is one of the most cost efficient milk producers on a per litre basis (Martin and Puangsumalee 2004). Along with most other dairy producing countries, the Australian dairy industry continues to undergo significant change (FAS 2006). The number of dairy farms has declined over the last 25 years, from over 22 000 in 1980 to about 10 000 in 2005 (ABARE 2006). Over the same period, average farm herd size has increased from 77 cows in 1980 to more than 200 in 2005 and average annual milk production per cow has increased from 2750 L to 5163 L (ABARE 2006).

A key driver of increased per cow productivity over the past 25 years has been the increase in supplementary feeding (Doyle and Fulkerson 2001; ABARE 2006) and increasing forage yields and quality due to fertiliser use, particularly N (Eckard *et al.* 2004). In 1980, most dairy farms were totally reliant on 'home grown' pasture and conserved forage. In 2004–05, 91% of all dairy farms used imported concentrates, with the average dairy farm supplementation greater than 1.1 t/cow.year, mostly as cereal grain-based supplements. The other major supplement brought on to dairy farms in Australia is hay, usually fed in equivalent amounts to grain. As expected, there is considerable variation in the amount and type of diet supplementation of lactating dairy cows, with grain inputs varying from 0 to 2.5 t dry matter (DM)/cow.year and forage inputs varying from 0 to 1.4 tonne DM/cow.year (ABARE 2006).

The intensification of the Australian dairy industry has exacerbated nutrient surplus at the farm scale. Reuter (2001) concluded that most dairy farms across Australia are in net positive balance for N, P and K. There have also been several Australian studies investigating nutrient surplus at a regional scale. For example, Ho *et al*. (2002) estimated annual nutrient balances on three irrigated dairy farms in northern Victoria (Vic.) using a simple model of nutrient inputs (fertiliser, feed, irrigation water and rain, N fixation) and outputs (milk, stock, surface drainage, greenhouse emissions). N and P surpluses ranged from 130 to 360 kg/ha and 10 to 95 kg/ha, respectively. If the farming systems were intensified by increased stock numbers, imported feed and fertiliser use, it was estimated that these ranges could increase to 220–760 kg N/ha and 40–120 kg P/ha. Lawrie *et al*. (2005), in a study of seven commercial and research dairy farms in coastal New South Wales, determined that farm scale annual P surplus ranged from 1 to 127 kg P/ha. In south-west Western Australia (WA), Neville *et al*. (2005) determined that the medium annual P surplus from 44 dairy farms across three environmentally sensitive catchments was 17.7 kg P/ha. In Gippsland, Vic., annual N, P and K surplus on a typical dairy farm was estimated at 15 and 19 kg/ha for N and P, respectively (Reuter 2001).

Within Australia, the dairy industry continues to be mainly in the cooler and wetter, or irrigated southern coastal areas, which also support a rapidly growing urban population. Increasing societal expectations for clean water and air, along with competition for land and water resources is likely to increase the tension between these competing interests.

Nutrient budgeting approaches and uses

A nutrient budget can be defined as an accounting approach for nutrient inputs, stores and outputs. Although there are a range of approaches to nutrient budgeting for farms, they can be classified into three major types, i.e. farm-gate, field and farm-system budgets (Oborn *et al*. 2003; Oenema *et al*. 2003). The choice of a budgeting approach depends on the intended purpose of the study, which in itself should also define the scale, the required accuracy, the data required, and the data collection strategy. These three different types of nutrient balances and the components generally included are represented in Fig. 1. The benefits, limitations and uncertainties associated with each of these different nutrient budgeting approaches has been summarised by Oborn *et al*. (2003).

A farm-gate budget operates as a simple accounting of nutrient inputs and outputs, and integrates farm scale information into an environmental performance indicator. A surplus or deficit can be adjusted for changes in stored soil nutrients and is often used to estimate loss, especially for N. Field budgets record nutrients that enter the soil surface and leave the soil via crop or pasture uptake. Field budgets are used for estimating the net loading of the soil with nutrients and can assist in refining soil nutrient distribution patterns within the farm. Farm-system budgets attempt to determine all nutrient inputs and outputs, transformations of nutrients within farm systems, and changes in soil nutrient pools. Farm-system budgets can be used to quantify nutrient loss pathways to water or air, either through direct measures or model predictions. These three budgeting approaches complement each other.

Farm-gate budgets are most common as they are generally easy to calculate from readily available data at the farm scale and from sources that are likely to be fairly accurate (Oborn *et al*. 2003). Fig. 1*a* illustrates the major inputs of nutrients (feed, fertiliser, animals, N fixation) and minor inputs (bedding, atmospheric deposition), and the nutrient outputs in products (milk, meat/animals, manure, crops) that are included in a farm-gate nutrient budget. A nutrient surplus or deficit can be calculated as the difference between total nutrient inputs and outputs per ha, usually determined over a calendar year. Whole-farm 'nutrient efficiencies' can be calculated as the total nutrients in exported products divided by the nutrients in inputs.

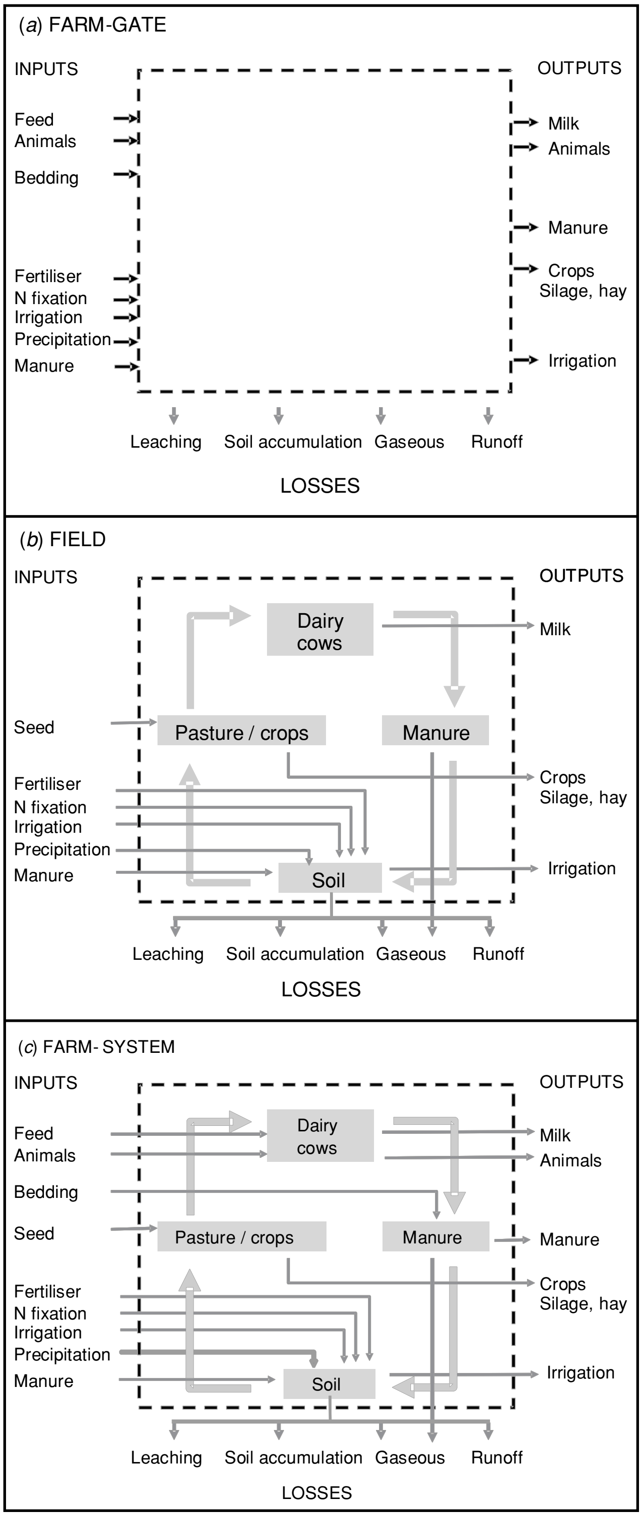

Fig. 1. Nitrogen and phosphorus inputs, outputs, losses and within-farm flow pathways for a typical dairy farm as required for (*a*) farm-gate, (*b*) field and (*c*) farm-system nutrient budgets.

Farm-gate nutrient budgets do not normally attempt to directly quantify environmental losses (Fig. 1) such as P and N runoff, P and N leaching, denitrification or N volatilisation, as these are difficult to measure and are highly variable in space and time (Oenema and Heinen 1999). Soil N is generally assumed to be in steady-state, and ‘surplus’ N is assumed to have been lost through gaseous losses or leaching. Surplus P may be accumulated in surface and sub-surface soil through soil fixation processes, although its fate is often difficult to determine (Burkitt *et al*. 2004).

Although farm-gate balances may assess nutrient accumulation and environmental risk, they do not describe the various internal transformations, storages, and distribution of nutrients within the farm (Fig. 1*c*). For example, a farm could be in ‘balance’ by having nutrient inputs equalling production outputs, yet also have substantial nutrient deposition onto a feed-pad which drains manure directly into a waterway. Moreover, the within-farm cycling of nutrients has resulted in nutrients being transformed from an environmentally benign form (feed) into an environmentally volatile form (urine, manure).

Nutrient budgeting has been widely adopted in the European Union (EU) (Goodlass *et al*. 2003), and the USA (Koelsch 2005), and more recently has been strongly encouraged and supported in New Zealand (Sneath and Furness 2006). Although there currently are fewer pressures or incentives within Australia to use nutrient budgets, and their use is low when compared with the EU, the USA or New Zealand, there is growing interest from advisors and farmers alike in using nutrient budgeting, particularly to assist with fertiliser management decisions. There is also growing interest from catchment management authorities and dairy companies, as nutrient budgeting is viewed as a useful tool in helping to achieve voluntary environmental nutrient management standards.

The benefits and relative simplicity of nutrient budgeting for dairy production systems has led to a large number of different tools and models being developed. A recent survey of agricultural ‘input–output accounting systems’ in Europe identified over 45 nutrient budgeting tools currently in use or available (Goodlass *et al*. 2003). There were substantial differences in complexity, scale, data requirements, methods, and how outputs were presented to the user. Many of the tools identified were still in the research or pilot stage, with only a few having a high degree of acceptance and farmer use, while none are formally audited or linked to any marketing schemes (Halberg *et al*. 2005*b*). Goodlass *et al*. (2003) concluded that most of the tools and documentation did not provide assistance with interpreting the outputs, nor did they suggest farm management options for improvements.

While there has not been any similar formal survey undertaken in Australia, there are several nutrient budgeting tools currently available to the dairy industry that have been tailored to Australian conditions. Most of these nutrient budgets are simple farm-gate approaches, dealing with P and K and have been developed by research and extension staff from state government agencies, private consultants, and fertiliser companies. Similar to the EU and the USA, they have generally been developed without any comparisons or standardisation of data needs, methods or calculations.

Selecting the most appropriate nutrient decision support tools presents a significant challenge for most farmers and advisors, and, therefore, farmers generally utilise tools that are locally developed and recommended by people they trust (Melland *et al*. 2005). This may in large part explain the diversity of different nutrient budgeting tools available.

Applications of nutrient budgeting

Nutrient budgets have been used to define differences in nutrient accumulation at farm, catchment, state, country and even global scales (Bennett *et al*. 2001). At the state scale, Mekken *et al*. (2006) calculated P budgets for all major agricultural land uses in New York State between 1987 and 2002, and concluded that the state's P surplus had substantially decreased from 23 million kg P in 1987 to 12 million kg of P in 2002. At the catchment scale, Neville *et al*. (2005) developed P balances for all agricultural enterprises in three water quality degraded catchments in the south-west of WA to determine land use specific nutrient surpluses and efficiencies. Power *et al*. (2002) used the Overseer model (Wheeler *et al*. 2006) to assess current N and P surplus and potential N leaching losses, across three key catchments in New Zealand. Nutrient budgets were also used to calculate P and N surplus at the farm scale in the Cannonvale water supply catchment in New York State and then scale up nutrient surplus to estimate potential losses at the catchment scale (Hutson *et al*. 1998; Cerosaletti *et al*. 2004).

Most commonly, nutrient budgets are used at the farm scale to make comparisons of nutrient surplus and efficiencies between farms with different production systems, soils or climatic conditions, or to monitor changes over time. The Mineral Accounting System (MINAS) was used in the Netherlands to determine nutrient surplus and potential losses from dairy farms with different milk production levels operating in three major dairy regions and on different soil types (Hanegraaf and den Boer 2003). Erb and Fermanich (2002) used the 'Dutch Yardstick' to compare nutrient balances on different sized dairy farms in Wisconsin. Neven *et al*. (2005) used nutrient budgets to demonstrate that N use efficiency on an average dairy farm in Belgium had increased by ~8% between 1989 and 2001. Several other studies (Ledgard *et al*. 2004; Neven *et al*. 2005; Wattiaux *et al*. 2005) used nutrient budgets to compare nutrient efficiencies or surplus for different types of dairy operations in different countries.

On a smaller scale, Gourley (2004) used a nutrient budgeting approach to examine the effect of stocking rates and rainfall on K and P balances in a dairy farm system study in Australia. As the stocking rate increased, so did the reliance on supplementary feed, resulting in an increasing surplus of both K and P. Similarly, dry conditions increased P and K surplus, with returned K in manure being equivalent to around three times the annual fertiliser requirement (Table 1). Ledgard *et al*. (2004) used a farm-gate nutrient budgeting approach to determine N use efficiency in a farmlet study, which compared zero N with high N fertilised dairy pastures. They concluded that despite the 46% increase in milk yield from the farm, N use efficiency fell from 43 to 23%, and N surplus increased from 92 to 387 kg N/ha.year.

Although the primary purpose of using nutrient budgeting is to reduce nutrient surplus and potential for loss to the environment, evidence of a direct link between nutrient budgeting and reduced nutrient surplus at the farm scale, and reduced environmental losses at the catchment scale is scarce (Halberg *et al*. 2005*b*). The results from the De Marke research farm and the 'Cows and Opportunities' project in the Netherlands (Neeteson 2000; Oenema *et al*. 2001) have shown that reduced N and P in groundwater can be attributed to using the MINAS system on dairy farms.

Weaver *et al*. (2005) used a farm scale P budget approach and geospatial scaling to calculate potential loads of P from farms in the Peel-Harvey catchment of WA. Taking into account assimilation and transport within subcatchments, they found a strong positive relationship between farm-gate P surplus and monitored P loads in streams. Cassell *et al*. (2001) developed a catchment scale nutrient export model, which utilises a comprehensive mass balance analysis of P sources, retention, and flows within a catchment. Validation of this mass balance model in two catchments in the north-eastern USA suggested that the mass balance approach adequately predicted monitored P export loads in waterways.

Nutrient budgets have also been found to be useful tools in improving farmer knowledge about nutrient flows and potential losses from their farms, and can influence fertiliser and manure management decisions (Oenema *et al*. 2001; Hanegraaf and den Boer 2003; Ledgard *et al*. 2004; Gourley 2004; Halberg *et al*. 2005*b*; Koelsch 2005; Currie and Hanly 2006).

Table 1. Potassium and phosphorus inputs in feed, outputs in milk, and difference, for three stocking rates (2, 3 or 4 cows/ha) in a wet (1998–99) and dry (2000–01) season in Victoria, Australia

	1998–99			2000–01		
	2 cows/ha	3 cows/ha	4 cows/ha	2 cows/ha	3 cows/ha	4 cows/ha
			Potassium (kg/ha)			
Feed	28	52	74	39	107	184
Milk	19	29	36	20	30	36
Difference	+9	+23	+38	+19	+77	+148
			Phosphorus (kg/ha)			
Feed	7	15	23	9	22	38
Milk	10	15	19	10	16	21
Difference	–3	0	+4	–1	+6	+17

Data requirements and uncertainty

Despite the relative simplicity of farm-gate nutrient budgeting, there are a surprising number of modifications, assumptions, exclusions and inclusions associated with individual approaches. Dairy farm nutrient budgets almost always include inputs such as feed, milk and fertiliser, whereas other nutrient sources such as bedding, N fixation, atmospheric deposition, and irrigation may not be included. Exclusions are often justified when they are not relevant to the farm operations, (i.e. no irrigation, no legumes grown), or a relatively small overall contribution (i.e. bedding, atmospheric deposition), while others may rely on the assumption of steady-state conditions (i.e. animal numbers and mass). These assumptions are sometimes incorrect, leading to inaccurate estimates of nutrient surplus and efficiency, and they also do not allow for a more standardised and flexible farm-gate assessment. While most nutrient budgeting includes N fixation from legumes, it is interesting to note that the widely cited MINAS system from the Netherlands was primarily focussed on manure, feed and fertiliser, and did not account for N fixation (Van der Meer 2001). Another nutrient management program 'N-CyCLE' does not account for bedding, irrigation, or atmospheric deposition (Wattiaux 2001). While farm-gate budgets do not generally estimate leaching or gaseous losses, some have included diffuse losses in surface runoff (Lawrie *et al.* 2005) or leaching (Wheeler *et al.* 2006).

Another area of bias is the choice of methods used to collect data for the various components; both volume or mass, and the associated nutrient concentration. Often this is completed by a combination of farmer survey (to determine values for types and amounts of feed purchased and sold), milk, animal and crop/fodder sales, and 'book' values of nutrient concentrations.

The few studies that have evaluated the accuracy of farm survey data have concluded that the data is generally reliable. In studies in Wisconsin, USA involving 33 confinement dairy farms (Powell *et al.* 2006), feed and milk production data, and information on manure land spreading practices provided by farmers, was found to be consistent with established feed, milk and manure production relationships and other data on manure collection and losses. In a study to determine appropriate data collection methods for nutrient budgeting in Belgium, Mulier *et al.* (2003) also found that on-farm surveys provided reliable assessments of mass of feed, and volumes of milk, but in contrast to Powell *et al.* (2006), they concluded that information gathered about volumes of manure were not always reliable. These studies demonstrate the value of survey type assessments of on-farm nutrient management, but highlight the need for more research to determine accurate and rapid survey instruments to assess nutrient management practices and efficiencies.

There are often good reasons to use book values or established algorithms to estimate nutrient concentrations in feed and manure, and losses. This is appropriate where data is difficult to directly measure, e.g. in the case of atmospheric deposition, or where the contribution is likely to be small relative to other components, e.g. nutrient inputs and outputs in irrigation water. However, the use of local reference data is recommended where available, as regional differences in these indirect inputs can be substantial (Rotz *et al.* 2005). Additionally, book values are appropriate where these is little variation in concentrations in components, or where there is a high level of confidence in the provided concentrations (such as in commercial inorganic fertilisers). It is generally accepted that book values provide a reliable assessment of nutrient concentrations for livestock and milk P (NRC 2001; Mulier *et al.* 2003; Wattiaux *et al.* 2005). Nutritive values and mineral concentrations for most feed types are also available online and in published forms both in Australia (Jacobs and Rigby 1999; Anon. 2007) and overseas (NRC 2001). However, nutrient concentrations in grains and forages can vary substantially and may have a large impact on the resultant farm-gate nutrient budget outcomes.

N fixation by legumes may be an important N input in both pasture and mixed cropping-dairy operations. In pasture systems that include legumes, N input from fixation can vary between 10 and 270 kg N/ha.year but is typically between 80 and 100 kg N/ha.year (Ledgard 2001). The amount of N fixed from the atmosphere by legumes is difficult to measure directly due to spatial and temporal variability and the complexity of measurement techniques. Consequently, fixed values or ranges are often used (Mulier *et al.* 2003), or N fixation is predicted using established algorithms (Kristensen *et al.* 1995; Ledgard 2001), which are often incorporated into decision support tools and models (Power *et al.* 2002; Rotz *et al.* 2005). However, the importance of correctly estimating N fixation has been highlighted by Wattiaux *et al.* (2005), when they demonstrated that N fixation could contribute either 24 or 44% of the total N inputs on the same 18 Wisconsin dairy farms, depending on how N fixation was calculated.

There are continued calls for greater consistency and standardised methods to improve the confidence and applicability of nutrient budgeting (Sveinsson *et al.* 1998; Goodlass *et al.* 2003; Oborn *et al.* 2003; Oenema *et al.* 2003; Anon 2005; Halberg *et al.* 2005*b*). Of particular note is the need to reduce the potential uncertainties in data and quantify the overall uncertainty associated with any nutrient budgeting approach (Oenema *et al.* 2003). Further analyses of uncertainties in nutrient budgets will also help identify where further information is required and, therefore, will assist in identifying further research needs.

Using nutrient budgets to improve on-farm nutrient use

Although a simple farm-gate budget will identify a nutrient surplus or deficit, it will not describe the various internal transformations, pools and distribution of nutrients across the farm, which may be contributing to nutrient use inefficiency and adverse environmental outcomes. To address these issues, nutrient budgets are often compartmentalised into key internal processes and transformations (Sveinsson *et al.* 1998; Schroder *et al.* 2003; Wattiaux *et al.* 2005; Powell *et al.* 2006). The quantification of these components in farm-system budgets allows the calculation of 'internal' efficiency measures such as feed use, manure collection and storage, nutrient redistribution, and crop/pasture nutrient uptake, as shown within the farm boundary in Fig. 1*c*.

As the P and N content of milk and meat are fairly constant, feeding excess dietary P and N results in decreased nutrient use efficiency by the cow and an increase in P and N excretion in dung and urine (Satter 2001). Feeding high P content diets in confinement operations, in the belief that this will increase milk production and conception rates in dairy cows, has been a common practice in the USA (Powell *et al*. 2002), but has not been a widely adopted practice in Australia. However, high P concentrations in pasture-based diets, also results in increased P concentrations in manure. Aarons (2001) found that dairy cows grazing pastures with markedly different forage P contents (ranging from 0.15–0.50% P) as a result of different and long-term P fertiliser rates had corresponding P concentrations in dung ranging from 0.37 to 1.27%. Not only does excess dietary P result in greater P concentration in manure, but as the organic P fraction of manure stays fairly constant at around 0.6 g/kg of feed consumed (Rotz *et al*. 2005), it also increases the proportion of water soluble P (Dou *et al*. 2003), which in turn increases P losses in surface runoff (Ebeling *et al*. 2002).

The nutrient loads from dairy cow dung and urine deposition are high. For example the deposition of a single urine patch can apply the equivalent of between 500–1200 kg N and 200 kg K/ha (Rotz *et al*. 2005). Aarons *et al*. (2004*a*) measured P and K application rates equivalent to 248 and 782 kg/ha, respectively from single dung pads, and found that both soil P (Olsen P) and K (Colwell K) levels doubled in the 0–5 cm layer below a dung pad after 40 days.

The deposition of nutrients in excreta by grazing animals plays an integral role in pasture production and potential environmental risk. Low nutrient deposition may limit pasture production, whereas high nutrient deposition may contribute to herd health problems and significant sources of nutrient loss. Areas where cows excrete urine and dung can be divided into four types: (i) areas where cows are confined, such as milking shed, yards and feed pads (manure is typically collected from these areas); (ii) areas where cows choose (or are encouraged) to be in high densities, such as stock camps, shade and wind protection, gateways, watering points and feed and mineral supply (manure is typically uncollected); (iii) areas where cows are confined in high densities, such as laneways, feed pads, and sacrifice paddocks (manure is typically uncollected); and (iv) areas where cows are foraging (manure is uncollected). Nutrient deposition within these areas will also vary. For example, the practice of strip-grazing or rotational grazing small paddocks results in high animal densities and correspondingly higher dung and urine loads per ha at each grazing. Additionally, cows will visit and forage in some paddocks more frequently than others due to differences in pasture production, the ‘locking up’ of paddocks to conserve silage and hay, and management convenience for the farmer.

Nutrient loads from dung and urine are often extremely high in confinement areas as a result of the high density of cows held for extensive time periods. For example, if a 200-cow lactating herd typically spend around 10% of each day on a feed pad, they would excrete around 6.4 kg of N each day and 1.9 tonne of N over 300 days in this confined area. Despite the fact that 20% or more of Australian dairy farms have feed pads (Anon. 2001), nutrient accumulation and losses from these areas are often overlooked.

The redistribution of manure collected from yards and the milking shed is another reason for uneven nutrient distribution across the farm. While 80% of Australian dairy farms have effluent management systems (Anon. 2001), the management of this collected manure is generally poor. Effluent ponds are often not emptied on a regular basis, and the storage capacity may be too small for the effluent loads. Consequently, effluent ponds may overflow into adjoining paddocks and flow into drainage lines and waterways. Even when effluent is applied to pastures in a managed way, it is often applied to readily accessible areas, and the fertiliser value of the effluent is rarely accounted for.

The harvesting, storage and feeding of conserved forage are other key modes for transfer of nutrients within dairy farms. Assuming a ryegrass pasture in spring has around 40 mg/kg N, 25 mg/kg K, and 3 mg/kg P, a 3 t/ha hay or silage harvest would remove 120 kg N, 75 kg K and 10 kg P/ha. Although fed back to the cows, the nutrients in urine and dung are unlikely to be deposited back to these same paddocks.

The heterogeneous distribution of nutrients within Australian dairy farms has been highlighted in several studies. For example, Gourley *et al*. (2005) collected soil samples from all paddocks on 20 different dairy farms in Vic. and found substantial differences in P, K and sulfur soil test levels between paddocks on almost every farm sampled. Examples of soil P and K levels from three contrasting dairy farms are provided in Fig. 2. Typically, higher soil nutrient levels were associated with loafing paddocks, calving paddocks, and sacrifice paddocks near the dairy and where collected manure was applied. Soil fertility was generally lower in areas further away from the dairy, and where paddocks were regularly cut for hay and silage. Lawrie *et al*. (2005) also found widely varying soil fertility levels between paddocks on seven dairy farms in coastal New South Wales. On a commercial dairy farm, in Gippsland, Aarons *et al*. (2004*b*) found that nutrient levels in 33 distinct areas surrounding the dairy, laneways and stream were also highly variable, with Olsen P levels in loafing areas (0–5 cm soil samples) in excess of 210 mg/kg. All of these studies concluded that the uneven distribution and accumulation of nutrients in areas within the farm is unlikely to be generating increased production, as these areas often have soil test levels well above agronomic requirements, but may be contributing disproportionately to nutrient loss. However, these studies provided only limited information on the causes of the variability in nutrient concentrations within the farms and could not specifically identify the key fluxes of nutrients, resulting in the uneven distribution of nutrients.

A nutrient budgeting approach for the Australian dairy industry

We propose that a nutrient budgeting tool for Australian dairy farms not only needs to address the basic input and outputs of nutrients on dairy farms, but must also address the key internal nutrient cycling issues relevant to grazed dairy systems. These include the diets fed to dairy cows, which impact on manure nutrient loads and forms, manure nutrient distribution onto productive and non-productive areas, and manure nutrients that are collected, stored and redistributed. When combined with soil testing data, farm-system nutrient budgets can highlight the key pathways that are leading to the excess accumulation of nutrients within particular management units, quantify their relative efficiencies, and hence identify the opportunities to improve management and enhance environmental outcomes.

The development of a standardised nutrient budgeting approach is likely to result in improved nutrient management decisions by dairy farmers and advisors, enable appropriate comparisons and bench-marking and also serve as a useful educational, research and policy tool. It is proposed that a nutrient budgeting tool for dairy operations in Australia needs to:

(1) identify and quantify key nutrient inputs, outputs and stores (i.e. feed, manure) and nutrient surplus and efficiencies at both a simple (farm-gate) and more complex (farm-system) level,
(2) define the uncertainty around nutrient budget calculations and predictions,
(3) identify and quantify nutrient distribution within the dairy farm, and nutrient losses off the farm,
(4) integrate nutrient budgets at the field level with recommended Australian agronomic soil test targets and use this information to assist with fertiliser recommendations,
(5) provide an effective assessment of costs and benefits resulting from current nutrient management practices,
(6) establish appropriate targets for permissible surpluses and potential nutrient efficiencies at the whole-farm and component level, and
(7) provide recommendations on management practices, which will improve nutrient budgets and nutrient use efficiencies.

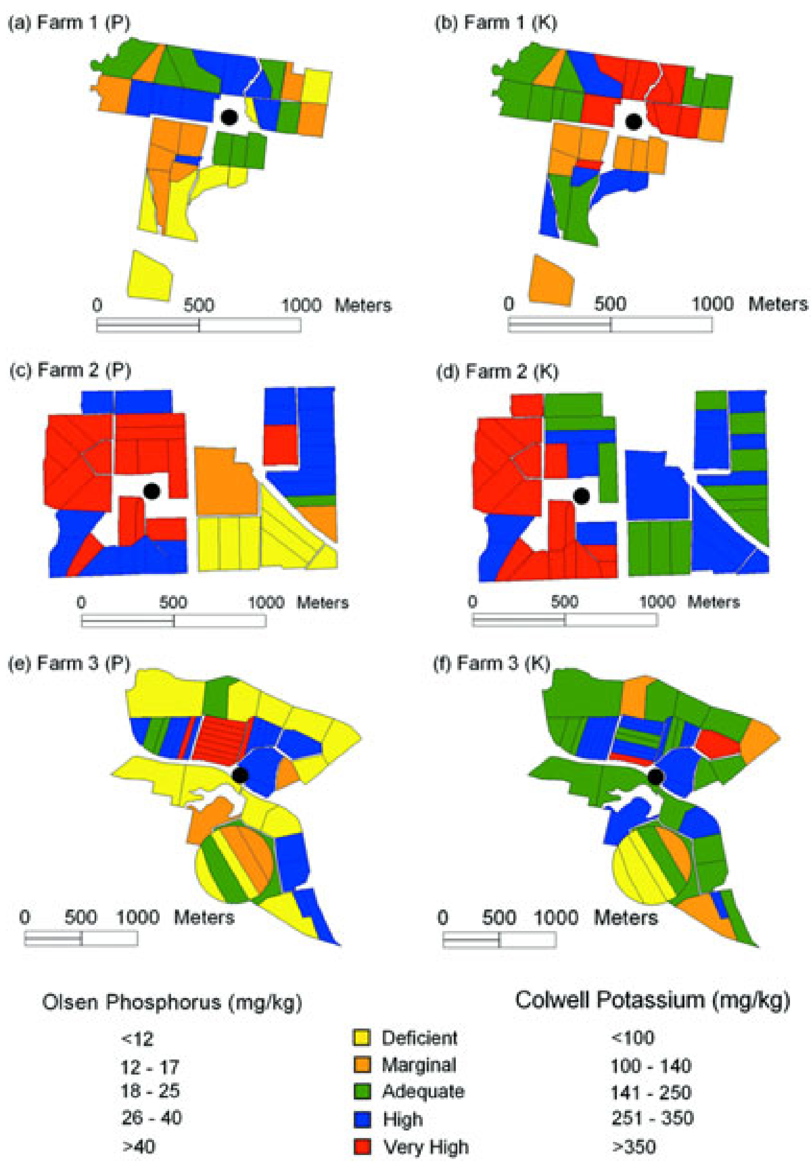

Fig. 2. Soil phosphorus and potassium concentrations for individual paddocks within three dairy farms in Australia. The legend reflects agronomic soil test recommendations for these two common soil tests. Farm 1 is from west Gippsland, Victoria, Farm 2 is from north-east Victoria, Farm 3 is from south-east New South Wales. The solid circle designates the position of the dairy shed within the farm.

Although no currently available nutrient budgeting model meets these requirements or is immediately suited to Australian dairy operations, there is still much to be learned from existing approaches. There is also substantial scope to improve future nutrient budgeting tools and models. The following principles and characteristics should assist in guiding the further refinement of nutrient budgeting approaches for the Australian dairy industry.

Improved understanding of applications

The selection of a nutrient budgeting approach should be based on a clearly defined research question and information need. This will determine the scale of assessment and identify appropriate methodologies. It is also important to identify the system boundaries, which include spatial (e.g. whole-farm, paddock) as well as temporal boundaries (e.g. yearly, seasonal, daily) for individual farm components. For example, the assessment of an average annual N balance from a dairy farm will require quite different information and methodologies, than field scale estimates of N leaching losses during a cropping season.

Standardisation of methodologies

There are currently many nutrient budgeting tools for dairy farms in use internationally, but there is a lack of consistency in the components included or in the calculations of nutrient inputs, outputs and internal fluxes. This issue is of particular concern due to potentially different outcomes and interpretations that may arise from different budgeting approaches, and the policy implications of these differences. Without a clear understanding of the assumptions and calculations used to define nutrient budgets, studies are difficult to interpret and compare. A standardised approach for the Australian dairy industry will improve the quality, transparency and interpretation of nutrient balances and will also allow for peer comparisons. Guidelines for international standardisation of nutrient budgeting approaches have been suggested (Oborn *et al*. 2003; Oenema *et al*. 2003) and should be adopted where possible.

Linking farm-gate nutrient balances with internal nutrient cycling processes and farm profitability

There is general recognition that farm-gate balances need to be complemented with the within-farm nutrient flows, transformations, and loss pathways. This improves the ability to identify key management practices and associated nutrient efficiencies within the control of farmers. Additionally, the monitoring of nutrient pools, such as soil nutrient levels, also provides a check of nutrient accumulation and links nutrient budgeting with agronomic nutrient requirements. Many nutrient management decisions also have an impact on farm profitability. More information on the costs and benefits associated with nutrient management decisions would provide an increased incentive for farmers to improve nutrient management practices.

Realistic expectations on gathering data

Nutrient budgeting as a tool to assist in nutrient management planning continues to be well received by farmers and policy makers due to the relevance and relative accessibility of information used, and the ability to integrate farm-based information into simple and easy to understand outputs. The developers of nutrient budgeting tools and models should keep in mind their key user groups, and ensure that the inputs and outputs are appropriate to the users. For farmers and advisors this means that nutrient budgets should continue to rely on reliable and easy to collect data. Additionally, the development of standardised on-farm record keeping systems that enable farmers and advisors to record relevant information at a time and place that suits their needs is likely to make data collection more efficient and accurate.

Improved recognition of uncertainties

Despite their relative simplicity and integrated outcomes (i.e. nutrient surplus/ha), nutrient budgets have a degree of uncertainty around the predicted outcomes due to biases and errors. For example, the use of book values for nutrient concentrations in imported feed and manure may not represent the actual concentrations. Even analysed subsamples of feed and manure may have analytical and sampling errors and biases. Studies involving nutrient budgets rarely present information about the uncertainty of the outputs presented. Oenema *et al*. (2003) suggested four steps in identifying uncertainties: (i) system analysis, to determine whether all relevant pools, inputs and outputs have been identified; (ii) classification of possible uncertainties, where nutrient sources are ranked in terms of the estimated degree of uncertainty; (iii) determination of uncertainty, where means and standard deviations of the various sources are determined; and (iv) calculation of the overall uncertainty of the nutrient budget.

Improved reference values and interpretation

The interpretation of nutrient balance information and internal nutrient use efficiencies needs to be done in a 'farming-systems' context and specific environmental conditions in which it operates. This benchmarking data is often scarce. For example, a farm-gate N surplus of 120 kg/ha may be interpreted as resulting from poor fertiliser and manure practices. However, additional information such as the minimum surplus achievable on these soils is 100 kg N/ha and that 50% of farms in the region have an N surplus of >200 kg/ha, changes the interpretation of this result considerably.

Rather than the unstated inference of achieving 100% nutrient efficiencies or 'no net surplus', the 'potential' nutrient management standards for the whole-farm, or nutrient management components within the farm (i.e. feed nutrient use efficiency, manure collection, pasture/crop nutrient use efficiency) are more appropriate assessment criteria. Standards may be determined from politically set targets, modelled expectations, and detailed experimental work under controlled conditions, but the goal or standard benchmark should be defined more realistically by 'best practice' from a larger dataset of farms with similar characteristics. It is suggested that farm nutrient budget information should be presented as the 'actual' performance *v.* the 'potential' performance, so that the information generated can be interpreted effectively and appropriately. Farmers and advisors should be able to benchmark particular farms' nutrient surpluses or deficits and efficiencies against a representative sample of similar farms. A better understanding of potential nutrient efficiencies would also better inform appropriate policy standards.

Linking nutrient balances to environmental impacts

Nutrient surpluses at a paddock level, and the subsequent accumulation and losses to the broader environment are often complex and highly variable throughout space and time. Excess P may be retained by soil and only slowly released through diffuse surface runoff processes, or alternatively lost in significant amounts during episodic erosion events. P movement from a farm may also be retained in sediment loads in streams and water storages, and only be released in sufficient quantities to cause water quality impairment under specific environmental conditions. Despite these complexities more evidence linking improvements in nutrient use efficiency and reductions in nutrient surpluses at the farm level, with improved environmental performance at the catchment or broader scale is desirable and would provide greater confidence to farmers, advisors and policy makers in the use of nutrient budgeting tools to enhance nutrient management and environmental performance on dairy farms (Neville and Weaver 2003).

Conclusion

There is no dispute that the Australian dairy industry in general is intensifying, with increasing stocking rates and a greater reliance on imported feed and fertiliser. Increasing nutrient inputs, the uneven distribution of recycled nutrients in manure among and within paddocks, and the accumulation of manure in non-productive areas, creates the potential for increasingly significant nutrient losses. Moreover, the low priority farmers generally give to nutrient management other than fertiliser applications, suggests that a structured approach to nutrient management is necessary for the Australian dairy industry.

Although none of the currently used nutrient budgeting tools available internationally are directly transferable to the Australian dairy industry, much can be learned from these existing nutrient budgeting approaches. The development of a standardised nutrient budgeting framework, on-farm method development, the quantification of various nutrient pools, and on-farm validation, will be necessary to provide a strong scientific and practical basis for a nutrient budgeting decision support tool for the Australian dairy industry. However, it must be remembered that nutrient budgets are just tools to assist decision making and policy approaches, and are not in themselves solutions to environmental problems. Improvements in nutrient management will also require leadership and commitment from all sectors, including the Australian dairy industry.

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